Beyond Standard Model in the top sector at CDF

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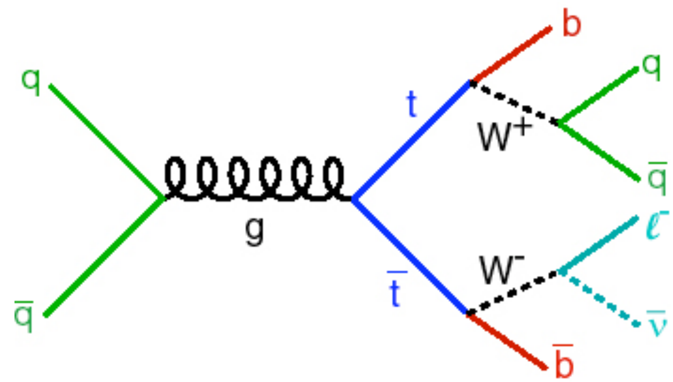
For the CDF collaboration

TOP2008, Isola d'Elba

BSM in the top sector

- TOP: Large mass , of the order of the electroweak symmetry-breaking (EWSB) scale
  - Tevatron combination: 172.6 ± 1.4 GeV/c^2
- special role in the mechanism of the EWSB?

  ⇒ Window on new physics



Exotic Decay modes:
- FCNC
- Charged Higgs

Resonant production
- search for new resonances or gauge bosons

New particles with top-like signature (admixture in top sample)
- Heavy top-like quark
- Scalar top

Exotic Decay modes

- FCNC
- Charged Higgs

Search for Flavor Changing Neutral Currents

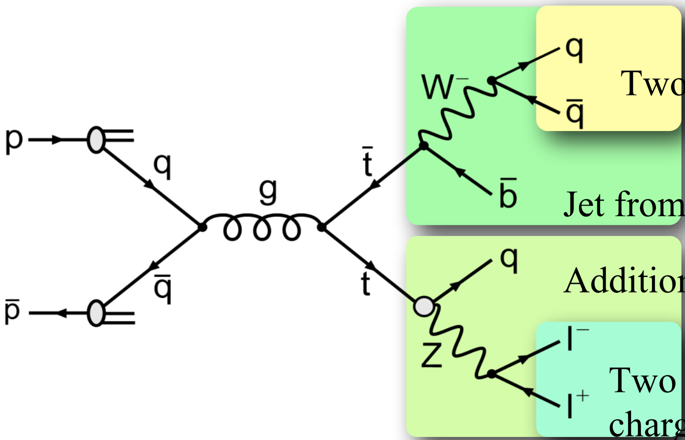
- In the SM, FCNC heavily suppressed.
  - BR($t \to Zq$) = O(10^{-14})
- New physics model predict higher branching fractions up to O(10^{-4}).
- Any signal of this rare decay
  $\Rightarrow$ new physics
  - Best published limit corresponds to BR($t \to Zq$) < 13.7%, from LEP

    Phys. Lett. B549 (2002) 290-300

Model	BR($t \to Zq$)
Standard Model	$\mathcal{O}(10^{-14})$
$q = 2/3$ Quark Singlet	$\mathcal{O}(10^{-4})$
Two Higgs Doublets	$\mathcal{O}(10^{-7})$
MSSM	$\mathcal{O}(10^{-6})$
R-Parity violating SUSY	$\mathcal{O}(10^{-5})$

[after J.A. Aguilar-Saavedra, Acta Phys. Polor **B35** (2004) 2695]

FCNC Search : Methodology



Two quark jets form W boson

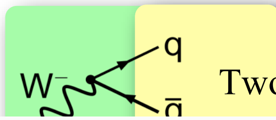
Jet from b quark, can be combined with W to form top quark

Additional jet, can be combined with leptons to form top quark

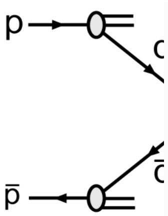
Two leptons (ee or μμ) with opposite charge, form Z boson

- Search in the ttbar →ZqWb ⇒ select Z+ >= 4 jets events
- Backgrounds: dominant Z+jets
- Discriminant: $\chi^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_W}\right)^2 + \left(\frac{m_{t\to Wb,\mathrm{rec}} - m_t}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_t}{\sigma_{t\to Zq}}\right)^2$

FCNC Search : Methodology

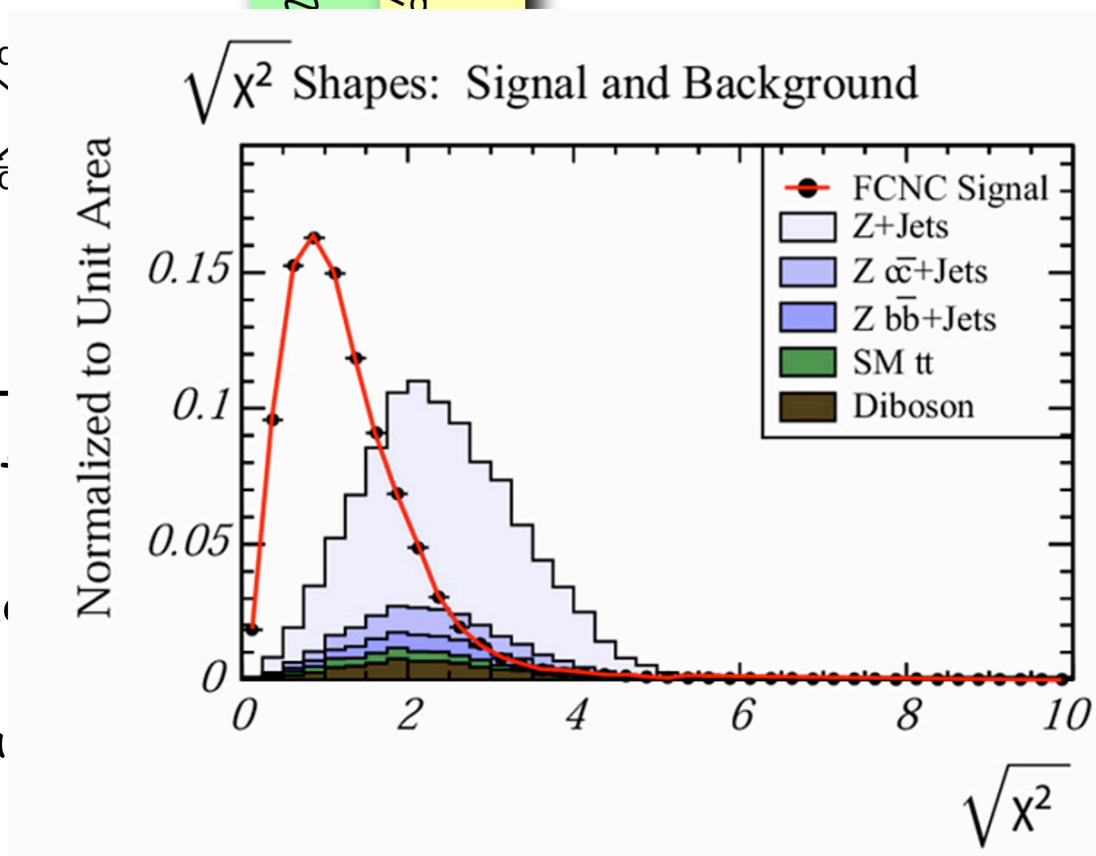


Two quark jets form W boson



top quark

n top quark



- Search in
- Backgroun
- Discrimina

$$\ldots_{\to Zq,\mathrm{rec}} - m_t \over \sigma_{t\to Zq} \Big)^2$$

FCNC Search : Methodology

Previous version: counting experiment

- Using two signal regions:
  - tagged and un-tagged
  - optimized selection cuts

⇒ Dependence on absolute predictions of backgrounds

Kinematic Variable	Optimized Cut
Transverse Mass	$\geq 200\,\mathrm{GeV}$
Leading Jet	$\geq 40\,\mathrm{GeV}$
Second Jet	$\geq 30\,\mathrm{GeV}$
Third Jet	$\geq 20\,\mathrm{GeV}$
Fourth Jet	$\geq 15\,\mathrm{GeV}$

New version performs a template fit:

- background normalization a free fit parameter
- but sensitive to shape uncertainties

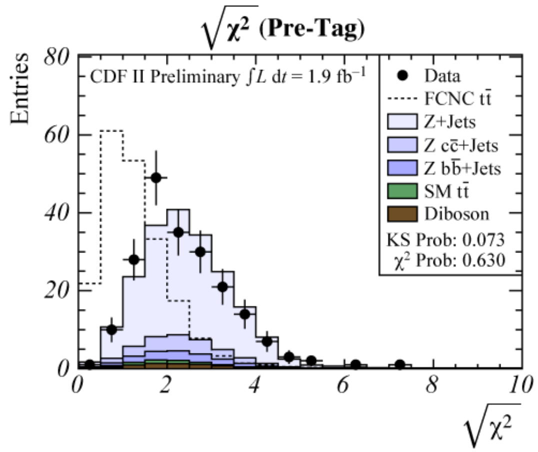
Add control region with large background acceptance

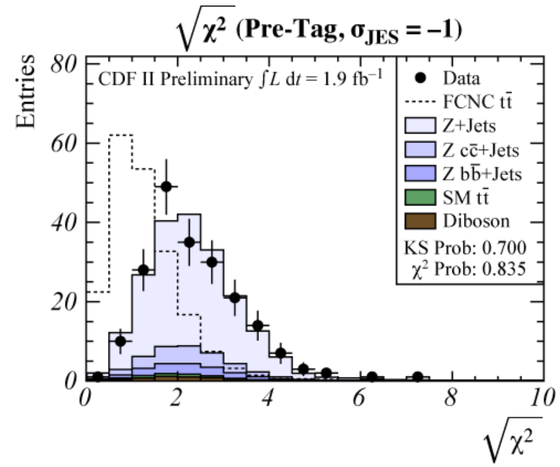
(events failing >=1 of the optimized cuts)

- Constraint on the background shape uncertainties (dominated by JES)
- Constraint Z+jets background

FCNC Search : Shape Systematic Uncertainties

Shape uncertainty: Choice of JES

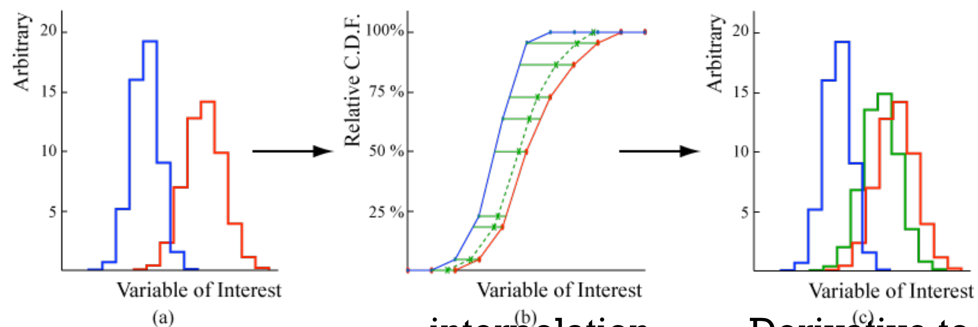




Data/MC comparison for nominal and -1σ JES
(5% shift on mean value $\sqrt{\chi^2}$ for Z+jets)

To handle the JES shape uncertainties: "horizontal morphing"

Fit treats shift as a continuous parameter by interpolating between templates at discrete shift values

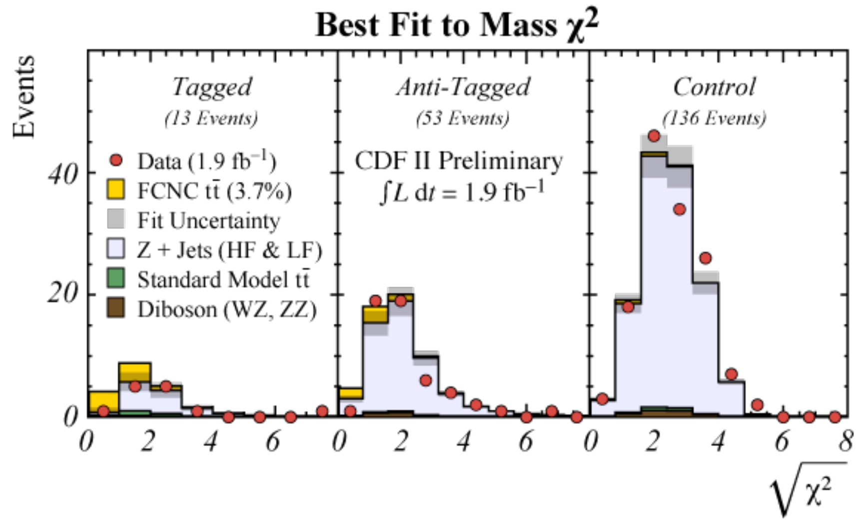


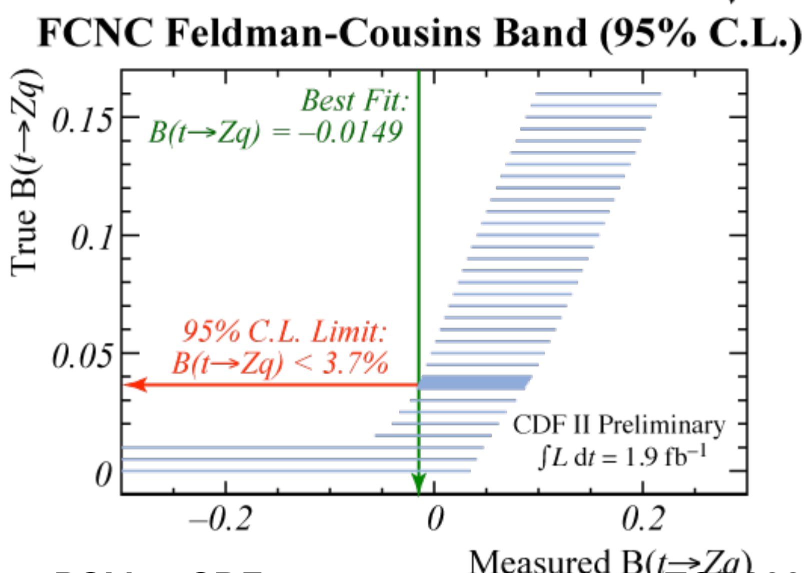
interpolation between C.D.F

Derivative to get morphed hist.

FCNC Search : Results

1.9 fb^{-1}





Simultaneous fit to the mass χ^2 distribution of two signal regions and 1 control one:

- B(t→Zq) = -1.49%
- Assuming B=0, p-value of 26.6%

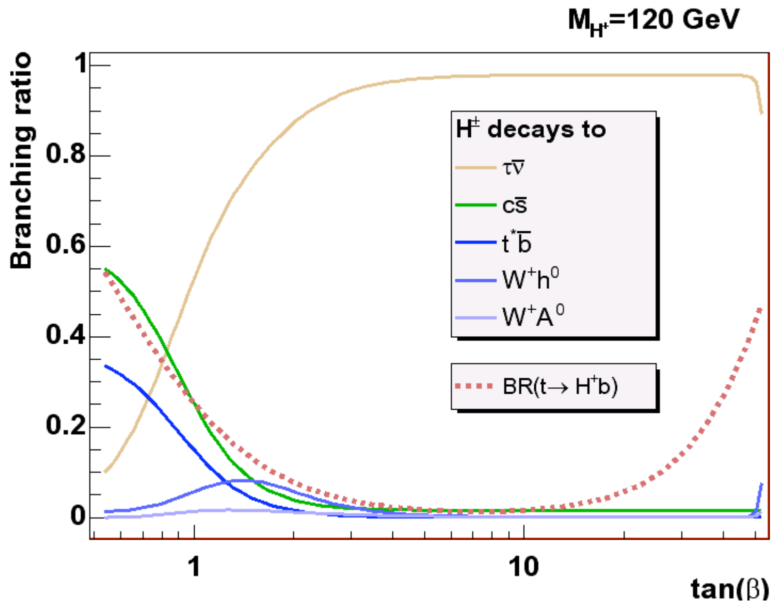
The upper limit is obtained from the Feldman-Cousins band :

- expected 5.0%

B(t→Zq) < 3.7% (95% C.L.)

Search for charged Higgs in top decays

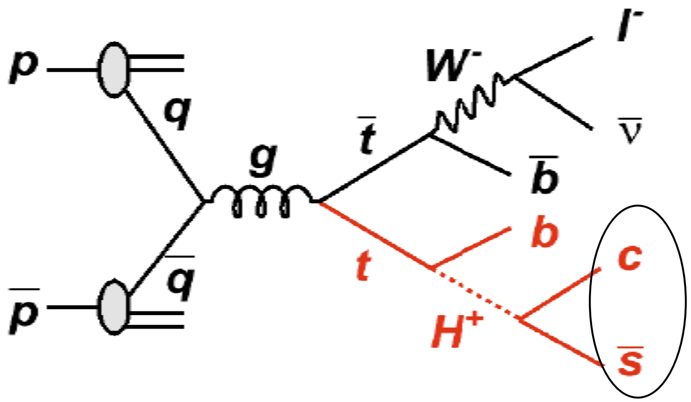
- In the Minimal Supersymmetric Standard Model (MSSM) :
  - BR(t->H⁺b) >10% for small and large tanβ
- At small tanβ, the H+ will predominantly decay to $H^+ \to c\bar{s}$
  - Masses larger than W boson have not yet been excluded by previous searches. **PRL 96, 042003 (2006)**



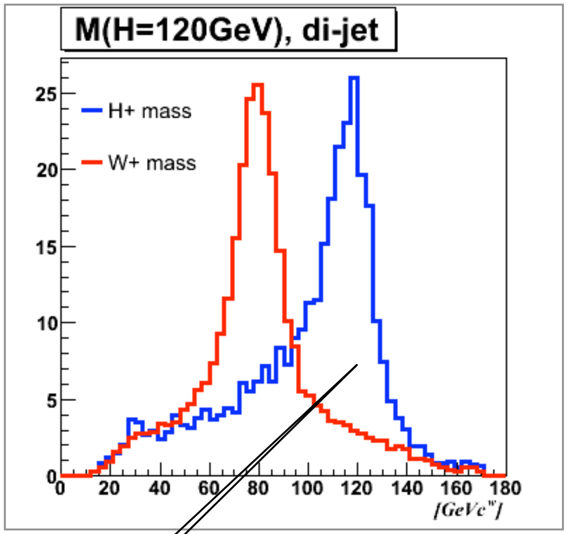
$CP_{super}H$
Comput. Phys. Commun. 156 (2004) 283, hep-ph/0307377

Charged Higgs search : Methodology

similar signature SM LJ channel



difference will show up on the dijet invariant mass



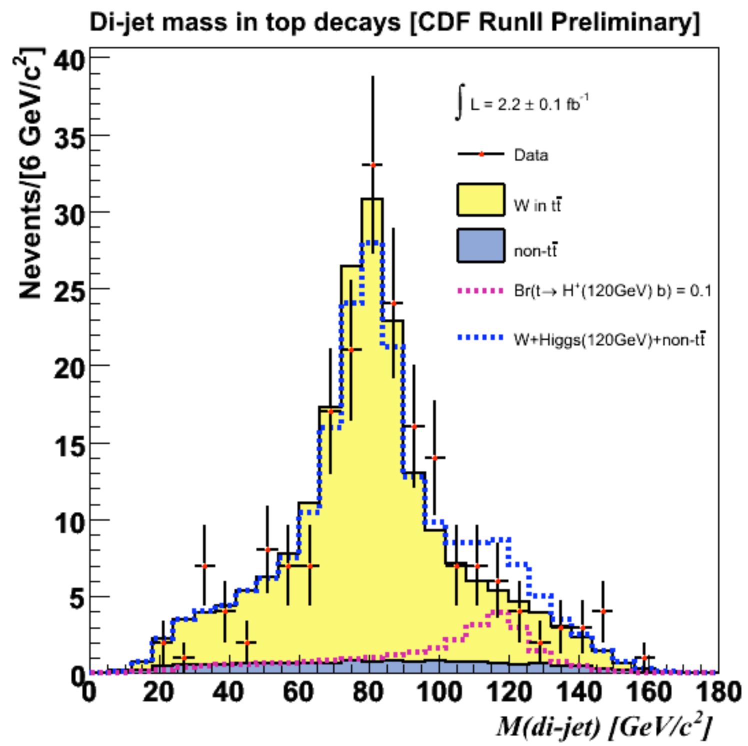
Reconstruct the event using a kinematic fitter

mass of the top and W constrained to 175 and 80.4GeV

$$\chi^2 = \sum_{i=l,4\,jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_T^{UE,fit} - p_T^{UE,meas})^2}{\sigma_j^2} + \frac{(m_{jj} - m_{jj}^{reco})^2}{\Gamma_W^2} + \frac{(m_{l\nu} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{bl\nu} - m_t)^2}{\Gamma_t^2}$$

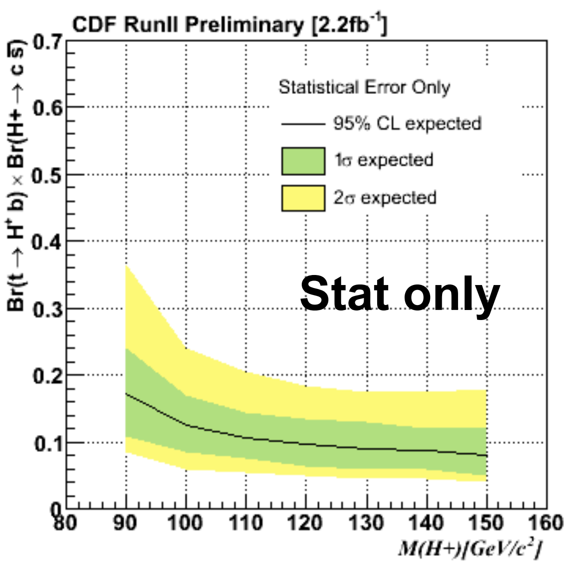
Charged Higgs search

- LJ channel, ≥ 4 jets, ≥ 2 b-tagged jets (200 events)
- Fit the reconstructed dijet-mass for the branching ratio



Dijet mass distribution including signal at 10% BR (mass 120GeV)

Charged Higgs search : Expected Limits

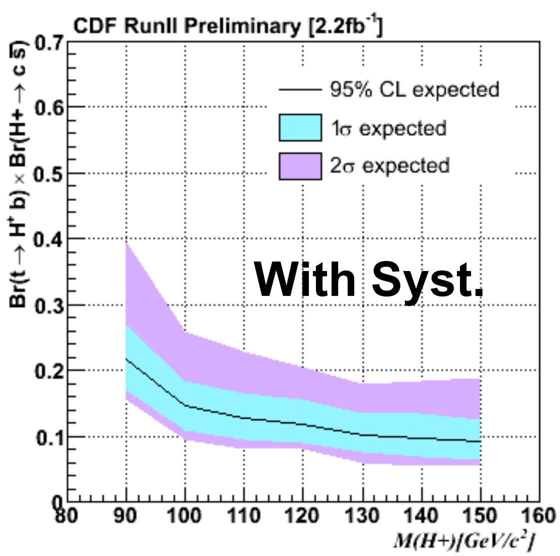


Systematic uncertainties included as shifts on branching ratio

draw PE from modified templates and fitted to nominal

dominant systematic: JES

Expected limits
no signal

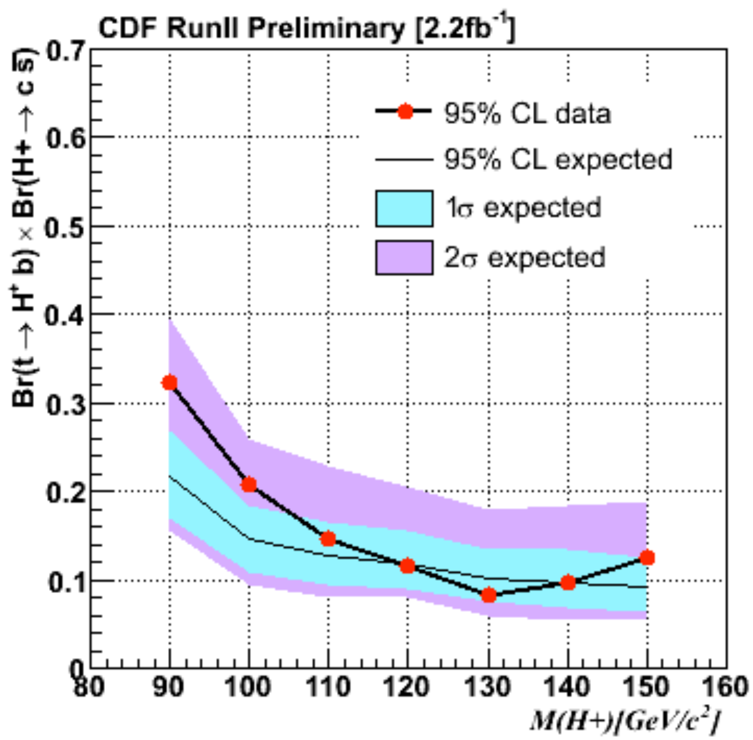


Statistically limited

Charged Higgs search : Results

2.2 fb^{-1}

Observed limits



Consistent with SM

Resonant production

Top quark Production

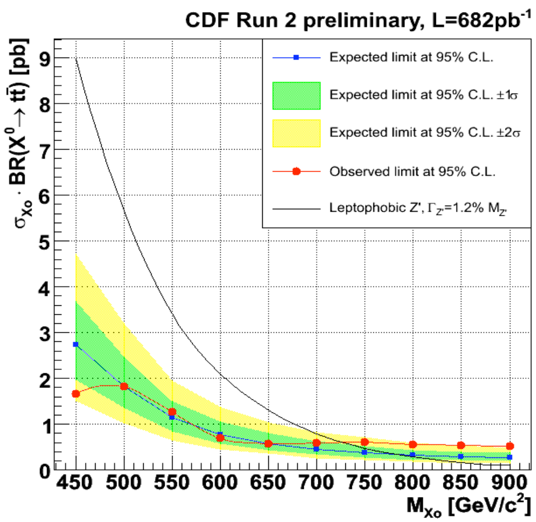
Top production cross section and distributions sensitive to new physics

Probe of new resonances or gauge bosons strongly coupled to top quark

(topcolor, technicolor, Kaluza-Klein states….)

Resonant $t\bar{t}$ production

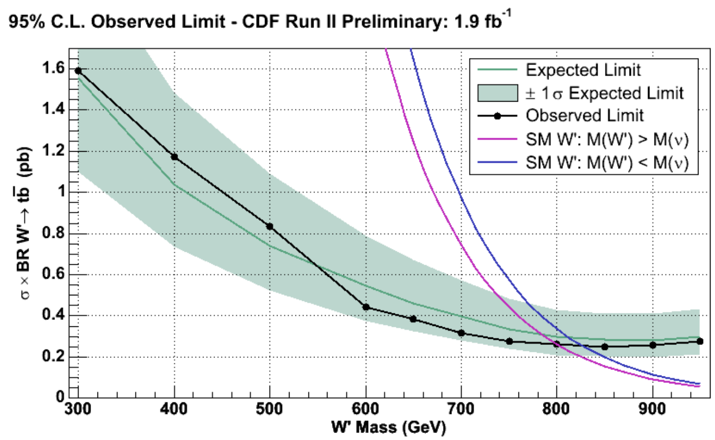
Search for narrow resonances in $M_{t\bar{t}}$



limit on a leptophobic Z', $M_{Z'} > 725 GeV/c^2$

Resonant $t\bar{b}$ production

Search for narrow structure in the M_{Wjj}



$M_{W'} > 800 GeV/c^2$ ($M_{W'} > M\nu_R$)

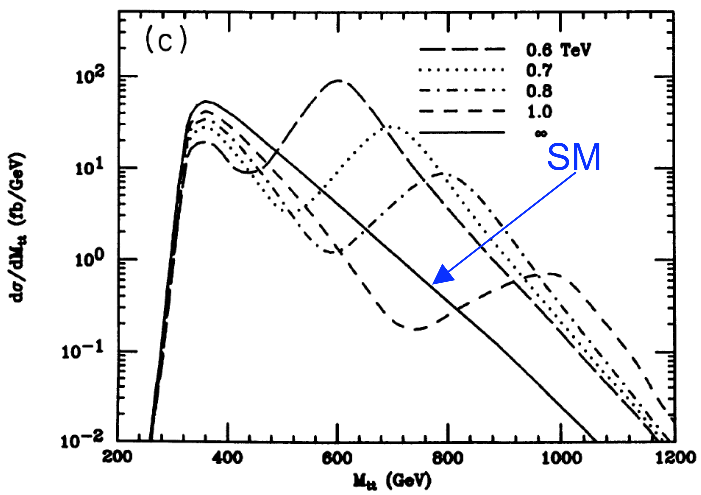
$M_{W'} > 825 GeV/c^2$ ($M_{W'} < M\nu_R$)

Top quark Production
Search for a Massive gluon

Search for new particles decaying to a top quark pair:

" Massive Gluon (G)"
- This process interfere with the SM $q\bar{q} \to t\bar{t}$

$\Rightarrow$ the $t\bar{t}$ invariant mass spectrum will be distorted by interference effects



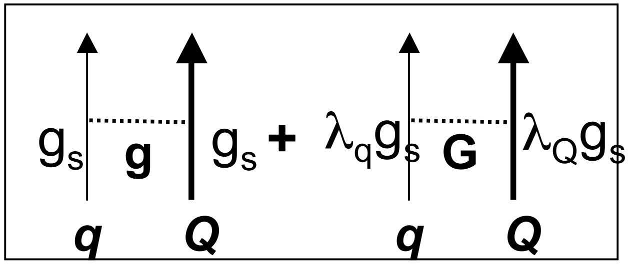
Not just a bump search

example of M_{tt} distribution
for a color-octet massive gauge boson
of Γ =0.2M_G, coupling =1 (mtop 160GeV)
Phys. Rev. D 49, 4454 (1994)
Christopher T.Hill, Stephen J. Parke

Search for a Massive gluon

- Define λ as the strength of coupling relative to the strong coupling
- Assume
  - no P-violation
  - SM top decay

$$Coupling: \lambda = \lambda_q \lambda_Q$$

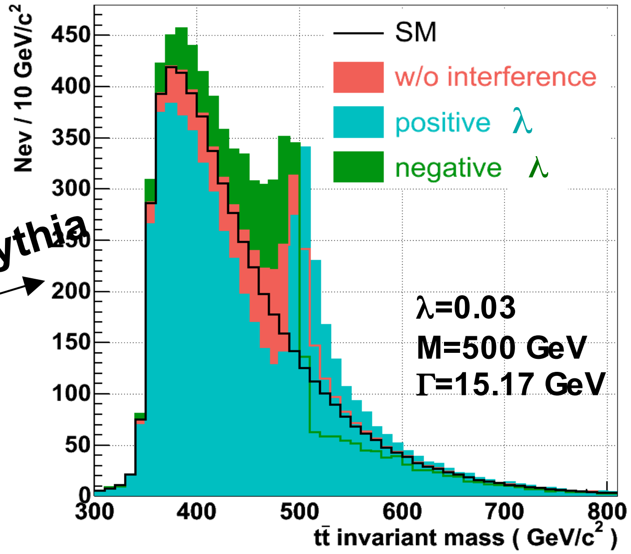


Production Matrix element
$\Rightarrow$ quadratic function of λ

$$\frac{|M_{prod}(MG)|^2}{|M_{prod}(SM)|^2} \equiv 1 + 2\lambda\Pi_{int} + \lambda^2\Pi_G$$

Dependent on Mass and Γ of G

Insert effect in Pythia



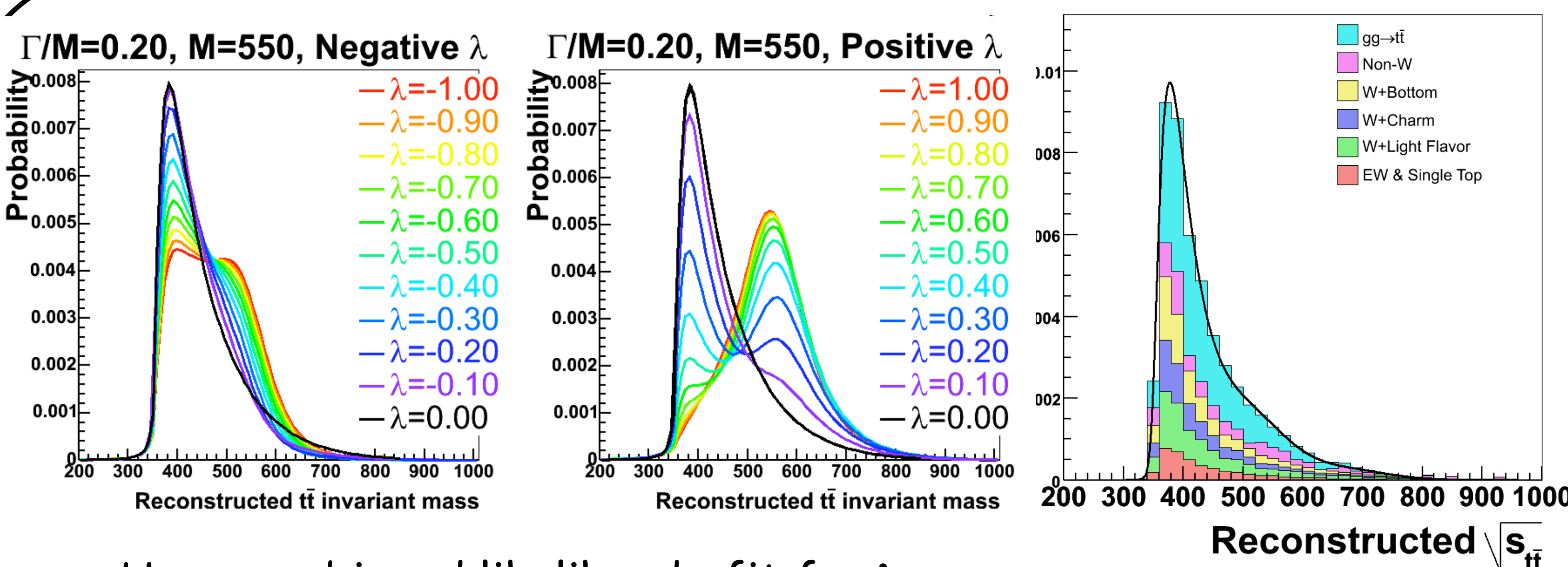
Assume no particular model $\Rightarrow$ Generic search on the (M_G, Γ) space

Massive gluon search: Methodology

In the L+J channel with 4 jets and 1 or more b-tags

- M_{tt} reconstruction: use the Dynamical Likelihood Method (DLM)
  - ✓ Profit from the experience on the top mass measurement
  - ✓ Adjusted method for this search by :
    - – Reconstruct the event-by-event $t\bar{t}$ invariant mass with a blinded production matrix element (set to 1).
    - – Define the invariant mass of the event as the mean of the event likelihood distribution
- Use an unbinned likelihood : fit for λ as a function of M_G, Γ
  - ✓ Define the probability density function for signal and background (signal: $q\bar{q} \rightarrow t\bar{t}$ (SM or Massive Gluon), Background includes $gg \rightarrow t\bar{t}$)
- Compare with the SM expectation. If consistent with SM, find upper/lower limits.

Massive gluon search: Methodology



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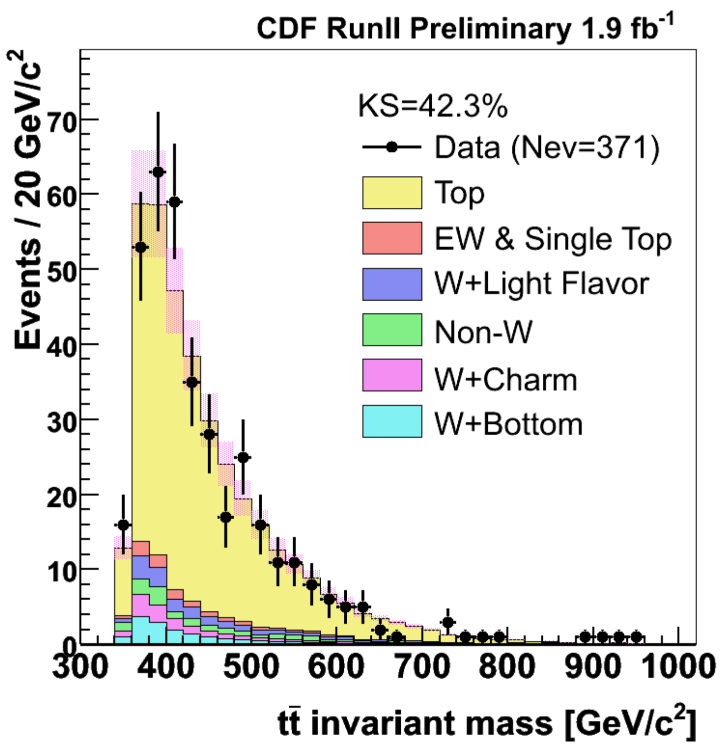
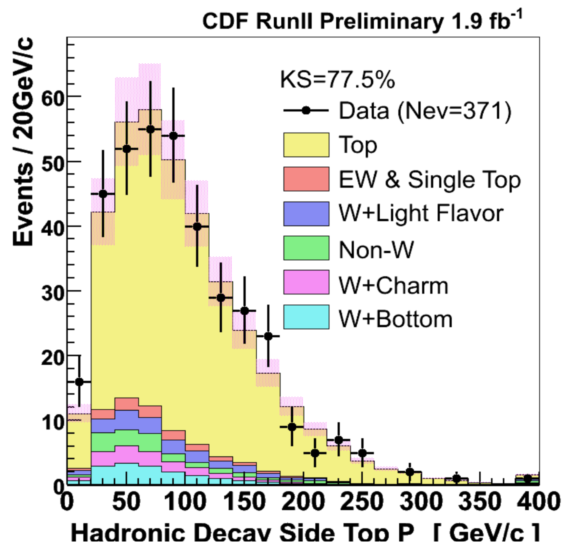
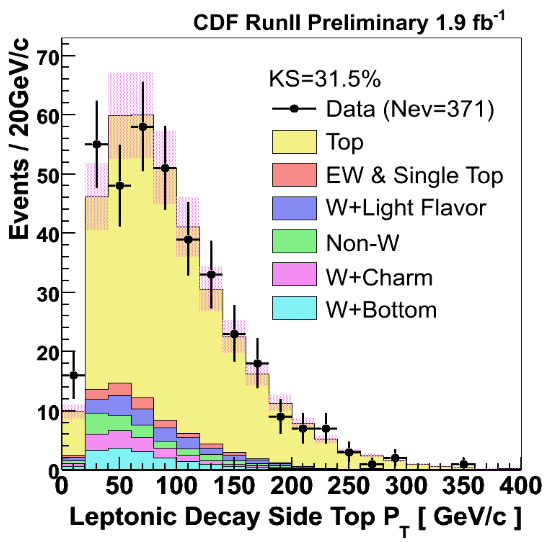
Massive gluon search



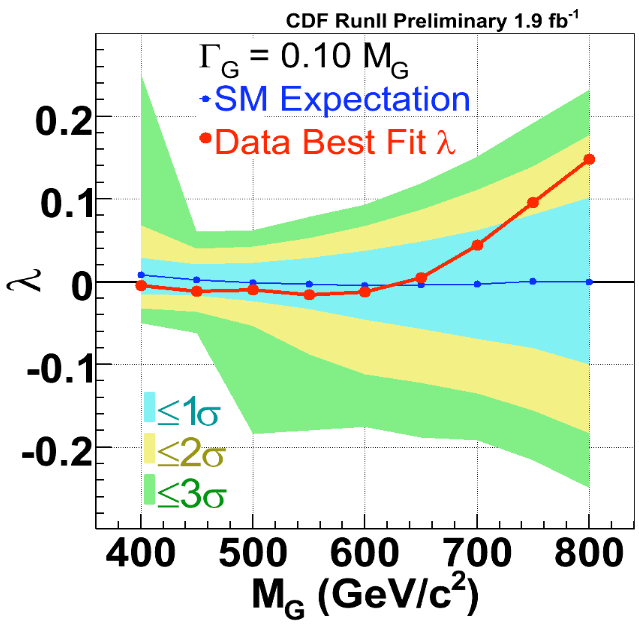




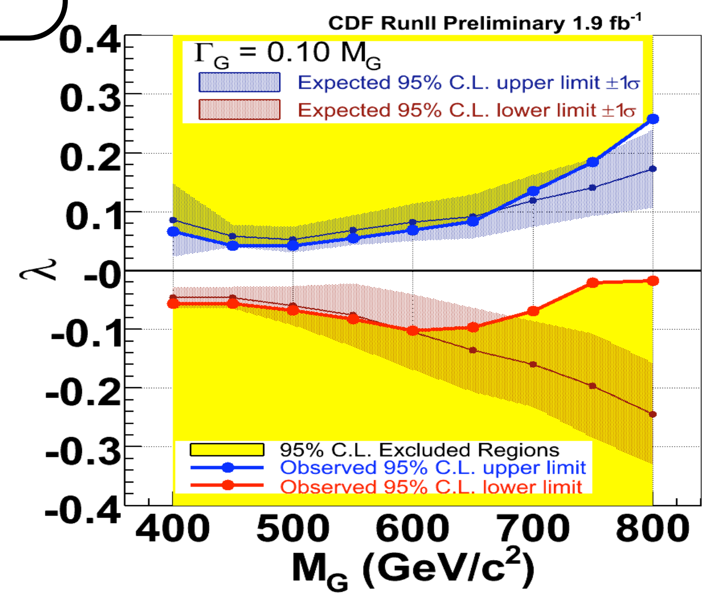
Massive gluon search: Results

1.9 fb^{-1}

Explored space:
$500 < M_G < 800$ GeV
$0.05 < \Gamma/M_G < 0.5$



Consistent with SM within 1.7σ



Limits dependent on Γ

New particles with top-like signature (admixture in top sample)

- Heavy top-like quark
- Scalar top

Search for heavy Top-like quarks

Production of new quarks decaying with similar signatures top quark pair

Introduced by theories:

- predicting 4-th generation of massive fermions PRD 64, 053004 (2001)
- Heavy top-like: Little Higgs PRD 69, 075002 (2004)
- Fermion doublets: Beautiful Mirrors PRD 65, 053002 (2002)

Assumed that new quark:

- t´ is pair produced strongly
- t' heavier than top
- t´ -> Wq

- model independent: estimate significance of potential excess in data
- if no excess, establish limit on the cross section for t' quark pair production

t' search : Methodology

- L+J channel, no tagging requirement (searching for t'->Wq)
  - Main backgrounds ttbar, W+jets and QCD
- 2D fit to the H_T vs M_{rec} data distribution

$$H_T = \sum_{jets} E_{T,jets} + E_{T,lepton} + \not{E}_T$$

  - M_{rec} is the reconstructed mass of the top quark
    - Use kinematic fitter (χ^2 function)
- Reduce the dependence on the QCD modeling:
  - applied a QCD removal cut:
    - E_T leading jet > 60 GeV
    - QCD is reduced by ~60%, signal reduced by ~10% at 240GeV

t' search : Methodology

$$\mathcal{L}(\sigma_{t'}|n_i) = \prod_{i,k} P(n_i|\mu_i) \times G(\nu_k|\tilde{\nu}_k, \sigma_{\nu_k})$$

Nuisance Parameters

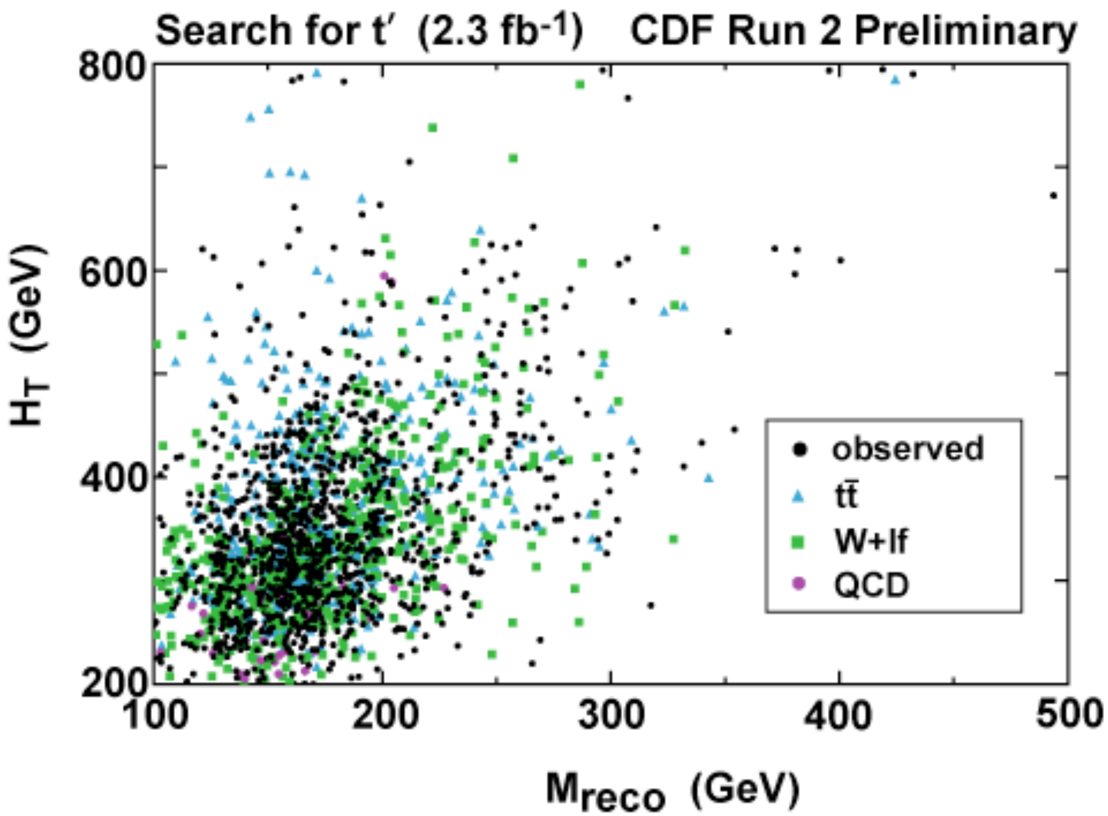
Parameters of the fit

- t': Varies freely
- Top: Constrained to SM cross-section
- W+Jets: Varies freely
- QCD: derived from data
  Fit insensitive to this contribution

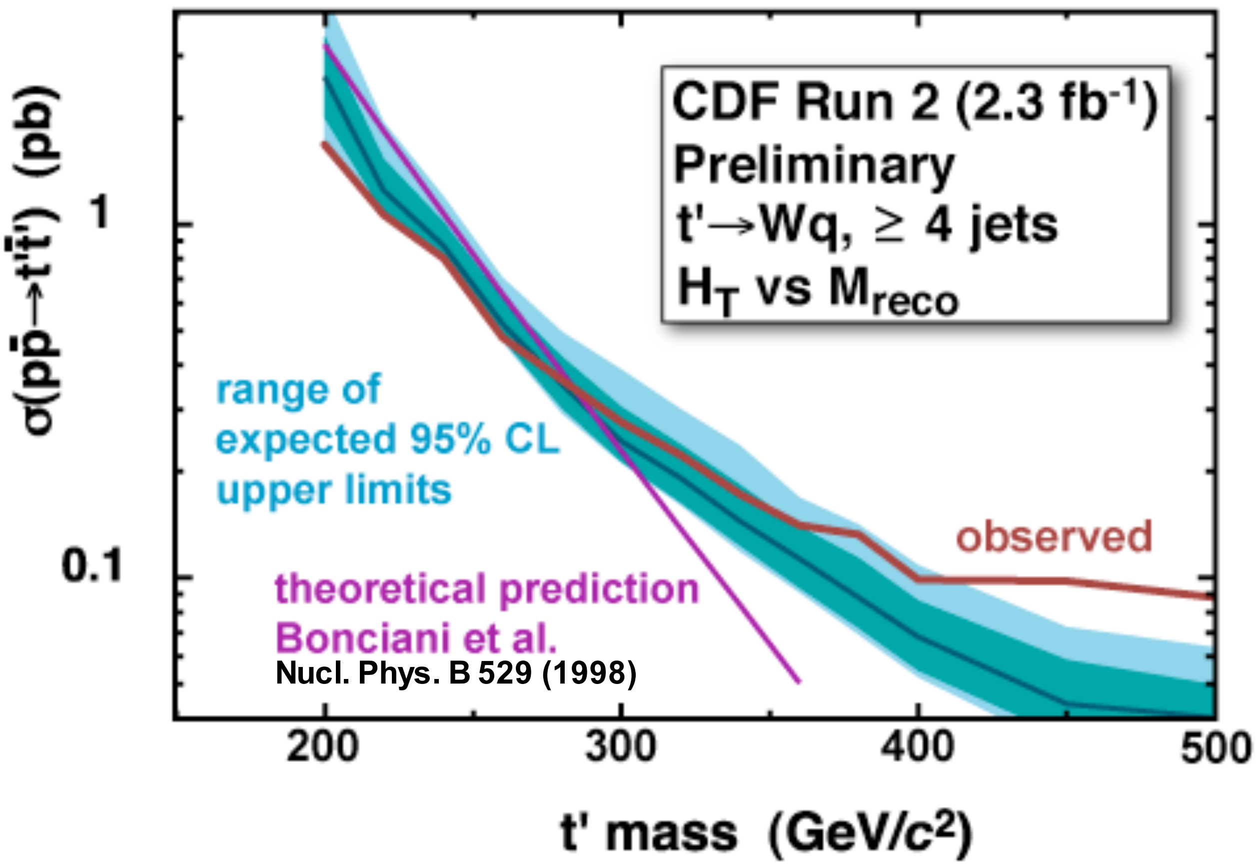
Systematics

- Included as shifts on $\sigma_{t'}$ (draw PE from modified templates and fitted to nominal)
  - dominant systematics: Q^2 scale for W+jets
- JES handled by template morphing
- Nuisance parameters are handled by profiling (maximize L).

t' search : Results



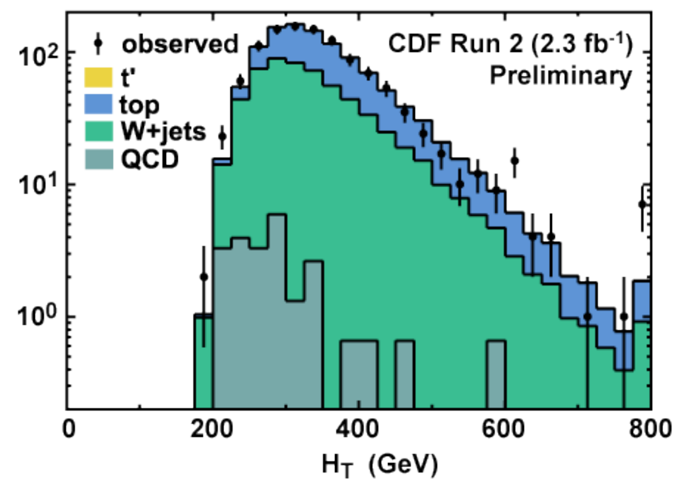
t′ search : Expected and Observed Limits



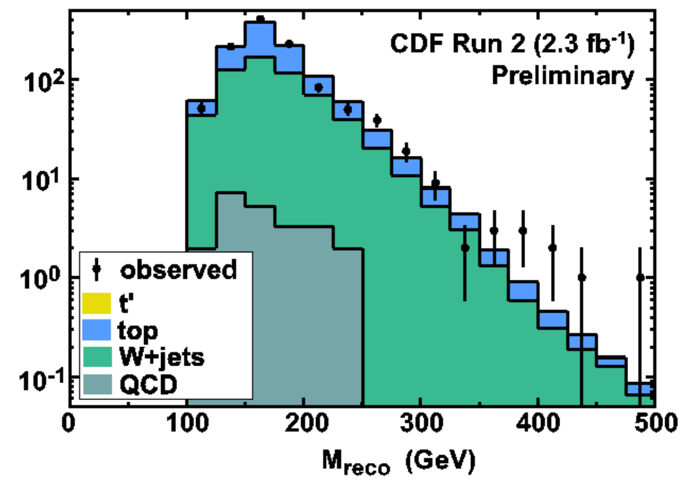
Exclude with 95% CL t´ mass below 284 GeV/c^2

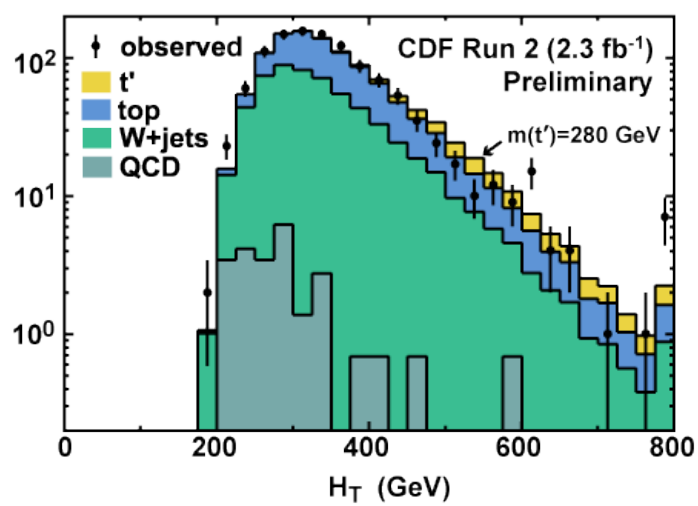
t′ search : H_T and M_{rec} Projections

2.3 fb^{-1}

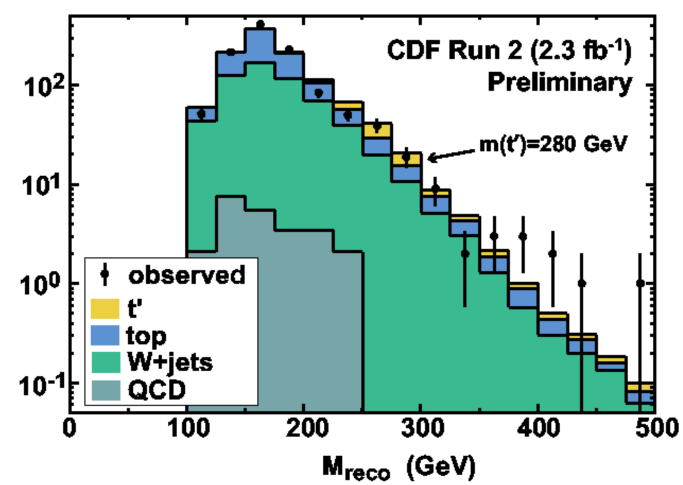


No signal





With t′ at limit



t′ search : Significant excess on the tails?

Group data in nxn bins of 25x25:

- Start from 1x1, 2x2, etc
- find SM expected number of events
- get significance (p-value) for the observed number

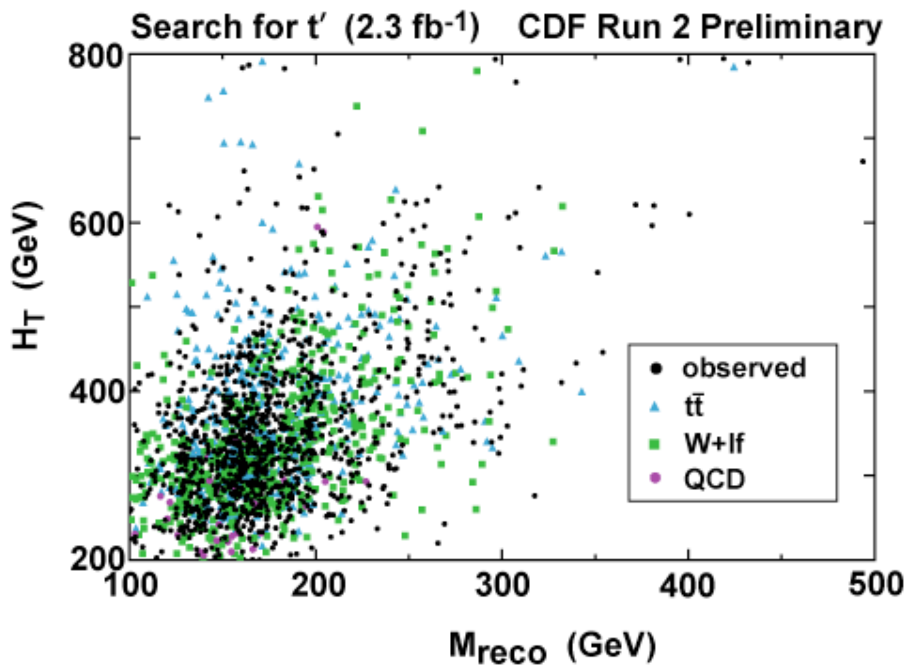
Find choice of larger significance:

→ 8x8

- 11 observed events
- 4.7 expected,
- p-value 0.0089

p-value for having observed 1 nxn bin with that or larger significance:

- "global" P-value = 2.8% ,
- Corresponding to ~ 1.9 σ



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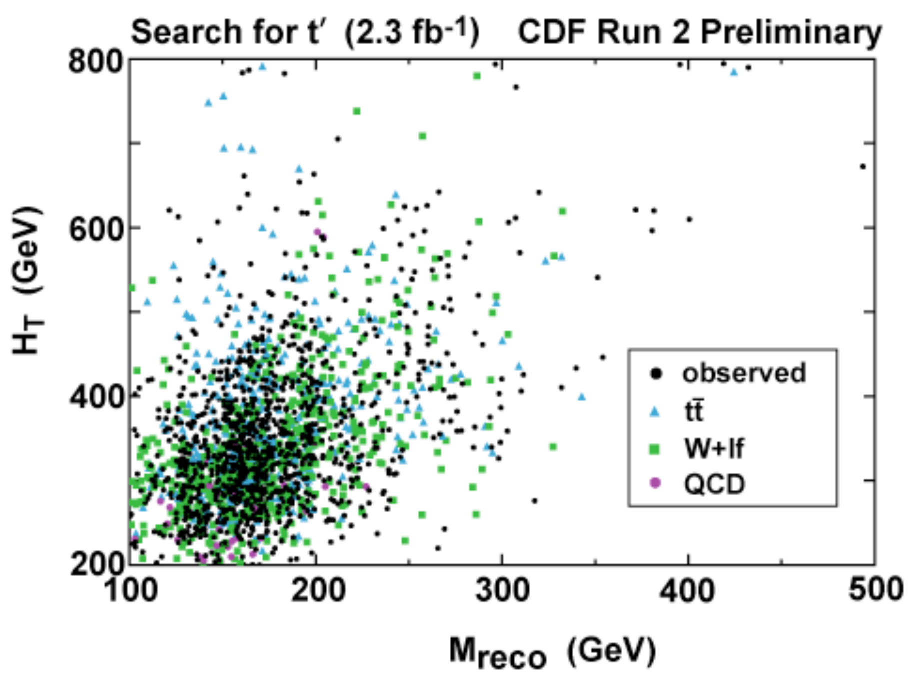


No significant excess observed

Search for pair production of Stop quarks

Within SUSY, a
very likely scenario: the lighter top
Superpatner is lightest than top
$\Rightarrow$ within Tevatron reach

Assuming:

$\tilde{\chi}_1^0$ is the LSP ← WMAP data

$m_{\tilde{t}_1} \lesssim m_t$ ← Electroweak Baryogenesis
C. Balazs, M.Carena, C. Wagner, PRD 70 (2004) 015007

$m_{\tilde{\chi}_1^+} < m_{\tilde{t}_1} - m_b$ ← - A possibility, otherwise $\tilde{t}_1 \to c\tilde{\chi}^0_{1,2}$

PRD D76, 072010

Decay

$$\tilde{t}_1 \to b\tilde{\chi}_1{}^{\pm} \to b\tilde{\chi}_1{}^0 W^{\pm}$$

$\approx$ signature of top quarks

Cross sections expected to be a magnitude lower than ttbar

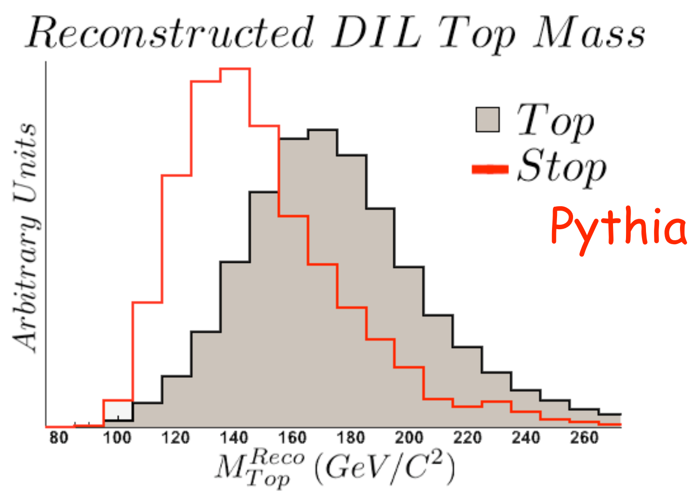
$\Rightarrow$ perform a kinematic analysis, explore the 3D phase space of these masses and place limits on the cross section of pair production stop

Search for pair production of Stop quarks

How stop events would behave under top event reconstruction?

Dilepton channel:

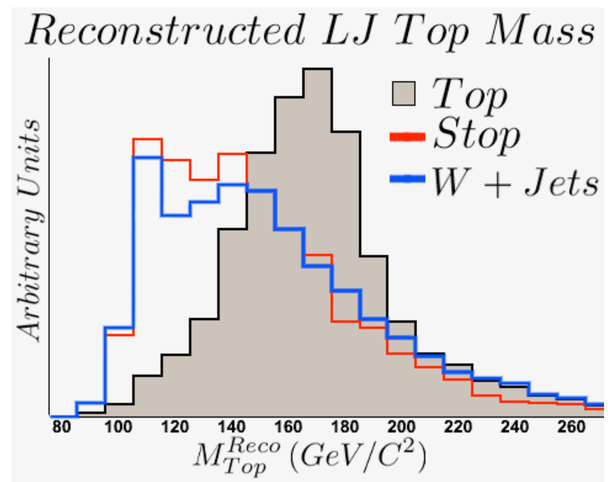
good signal:bckg



Bias mass to lower values

LJ channel:

large contributions from W+jets



indistinguishable from background

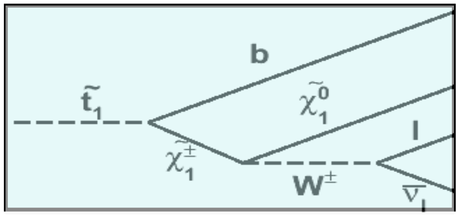
Perform the analysis on the Dilepton channel
Initial selection of >=2 jets and MET>20GeV.

Stop search: Mass reconstruction

Use a kinematic fitter.

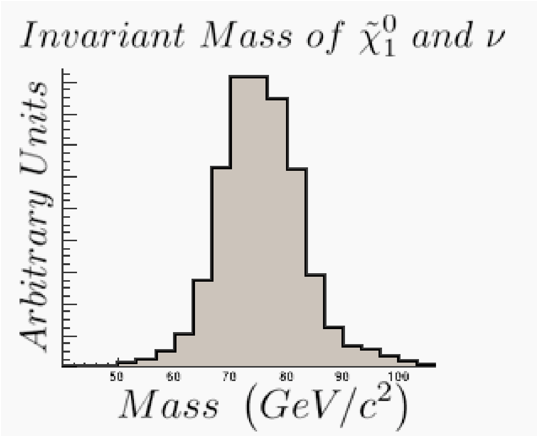
Solve for an under-constrained system

- Treating neutralino and the neutrino as a pseudo-particle :



Pair invisible particles into PP, Fix mass=75 Gev and width= 5 GeV

- Constrain chargino mass
- Minimize χ^2 for possible directions of PP for each leg (12x12 grid)
- Obtain mass as the weighted average



Stop search: Mass reconstruction

Use a ki

Solve fo

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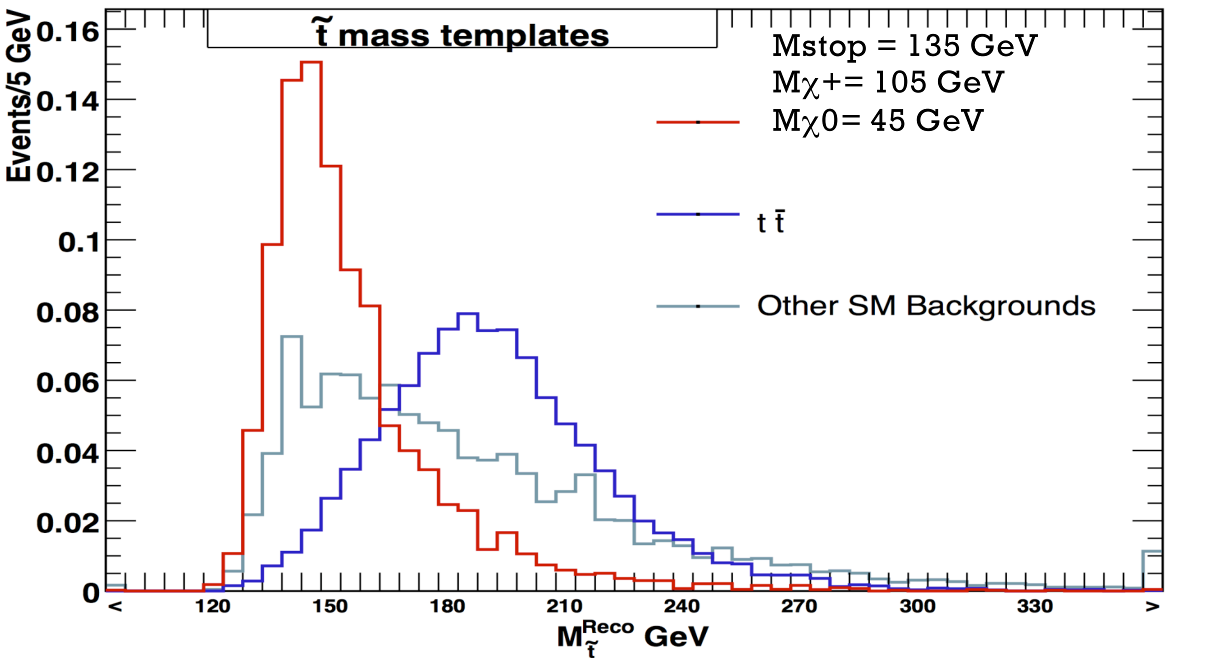
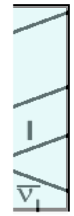
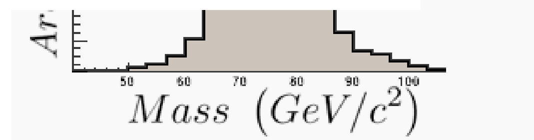




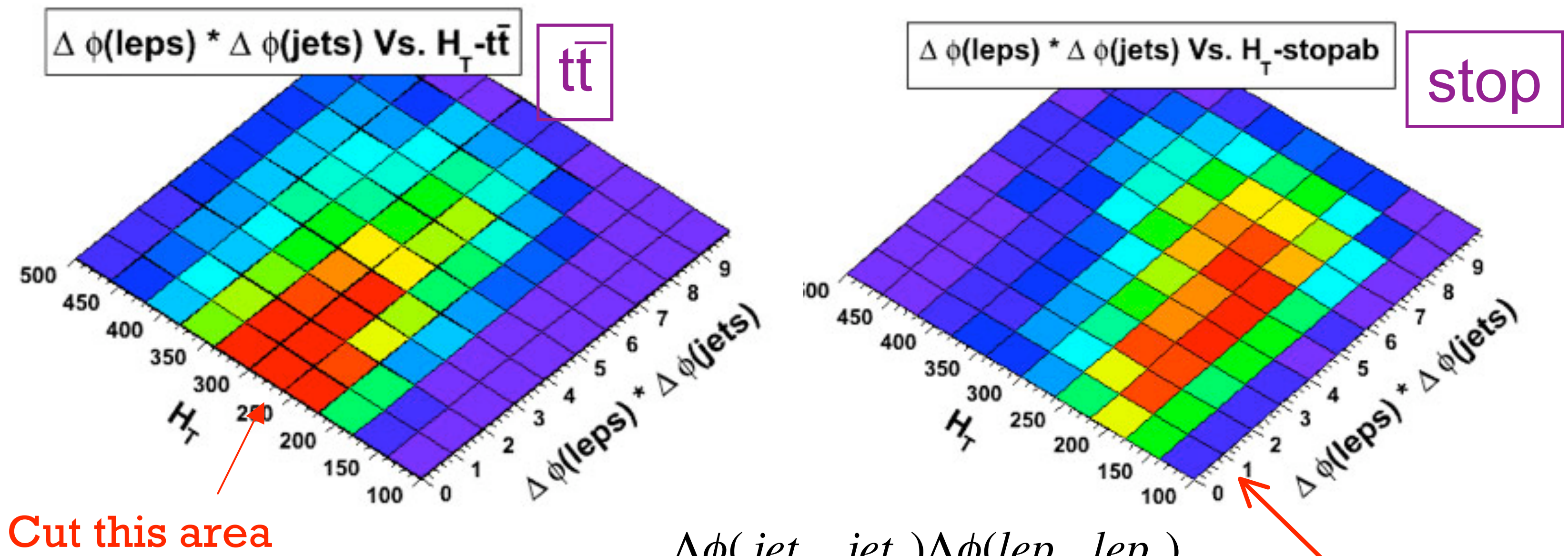
Pair invisible
particles into PP,
Fix mass=75 Gev
and width= 5 GeV



- Cor
- Min
PP f
- Obt

Stop search: backgrounds

Main background are top events



$$H_T < 215 + 325 \times \frac{\Delta\phi(jet_0, jet_1)\Delta\phi(lep_0, lep_1)}{\pi^2}$$

Kills ~50% of top with ~15% loss of signal.

Stop search: systematics and optimization

Template morphing:

- Treat shape systematics (largest JES)
  - nuisance parameter in the Likelihood
- Also to obtain mass templates between generated MC points

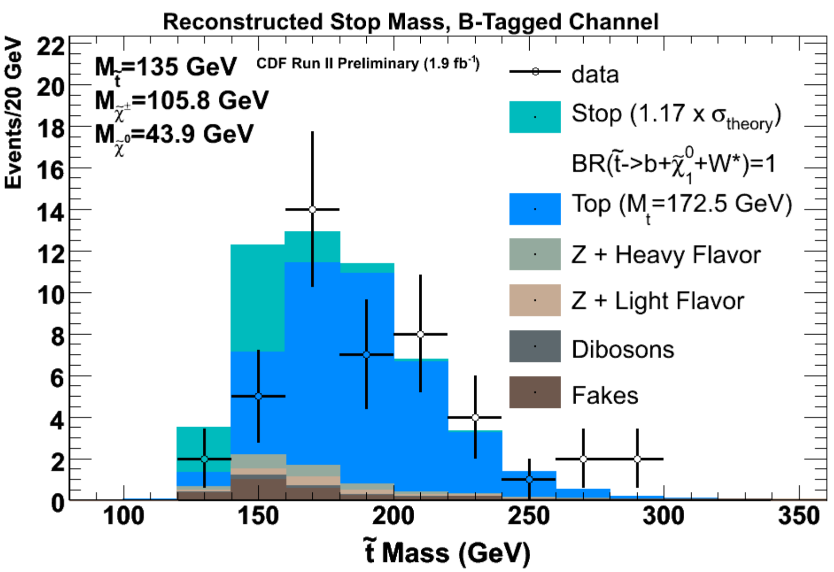
$$135\,GeV < m_{\tilde{t}} < 155\,GeV$$
$$105.8\,GeV < m_{\tilde{\chi}_1^\pm} < 125.8\,GeV$$
$$43.9\,GeV < m_{\tilde{\chi}_1^0} < 58.8\,GeV$$

Event selection:

-divide in tagged and untagged

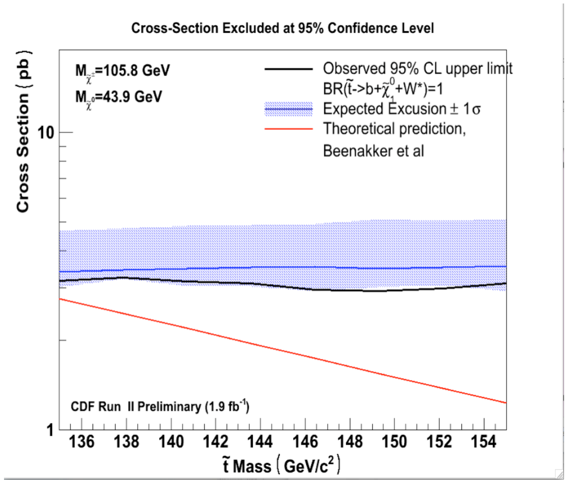
-optimized for each channel

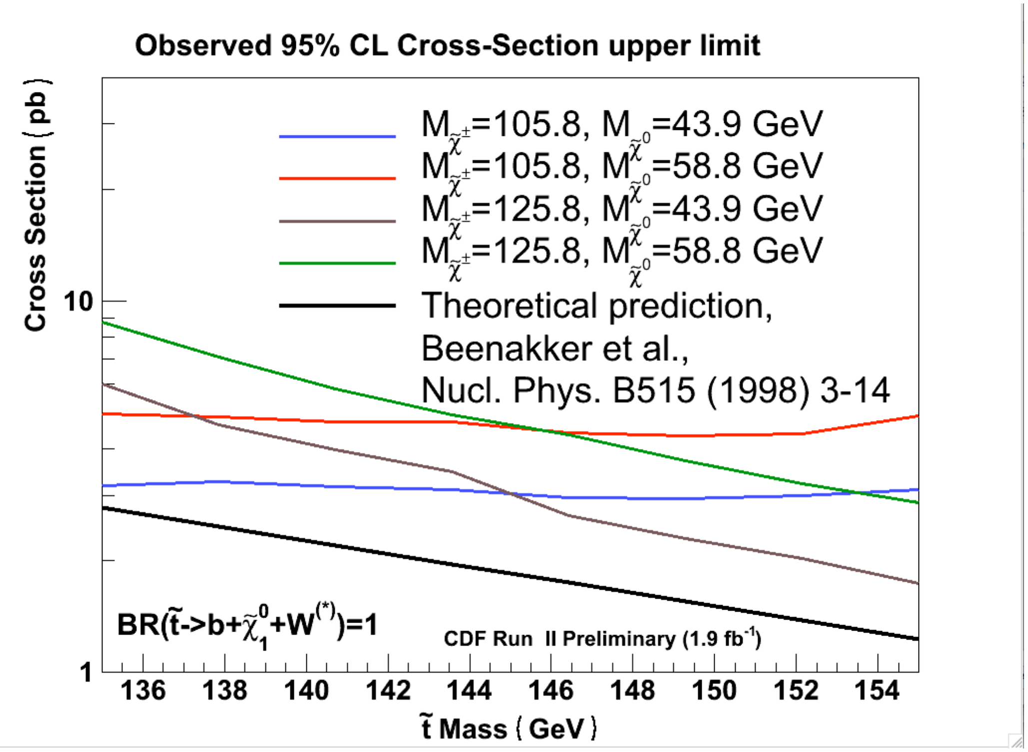
(jet Et, MET, top killer)



Stop search: Results

1.9 fb^{-1}



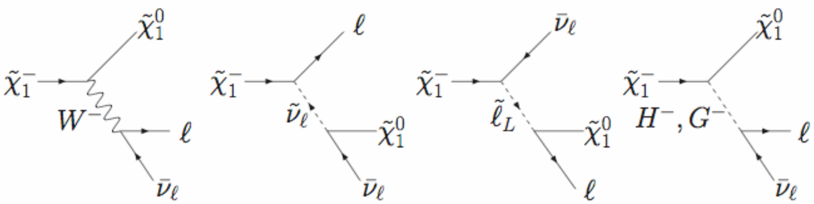


No evidence for stop found

Coming soon:

Change branching ratio assumption

Obtain 2D exclusion



Summary

No evidence of new physics, so far ....

- Larger samples available : $3.5 fb^{-1}$ on tape
- New and Updated searches coming soon

http://www-cdf.fnal.gov/physics/new/top/top.html

Tevatron

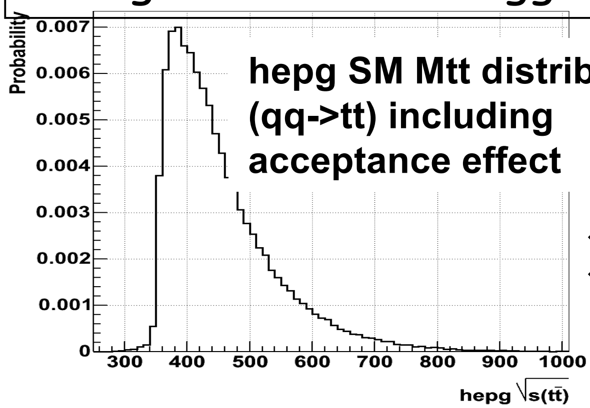
- Stringent tests of SM (qq->tt mode)
- Sophisticated analysis techniques
- Techniques to control systematics

LHC

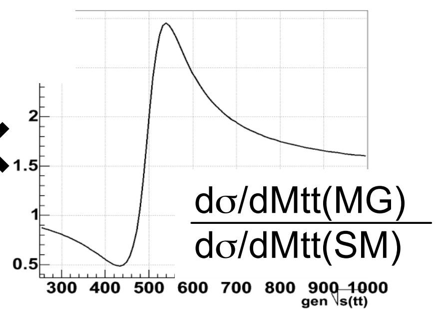
Backup

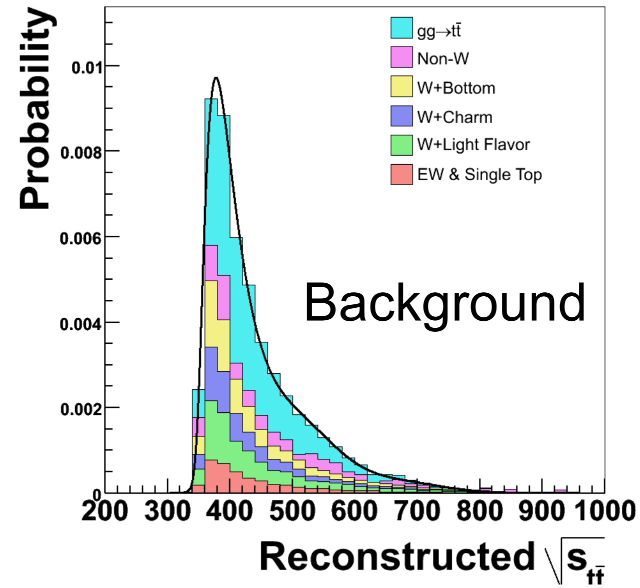
Massive gluon search: Signal and Background p.d.f.

signal: $q\bar{q} \to t\bar{t}$ (SM or Massive Gluon)
Background: includes $gg \to t\bar{t}$

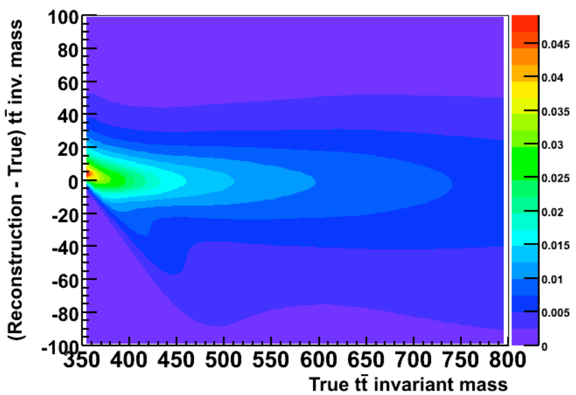


×

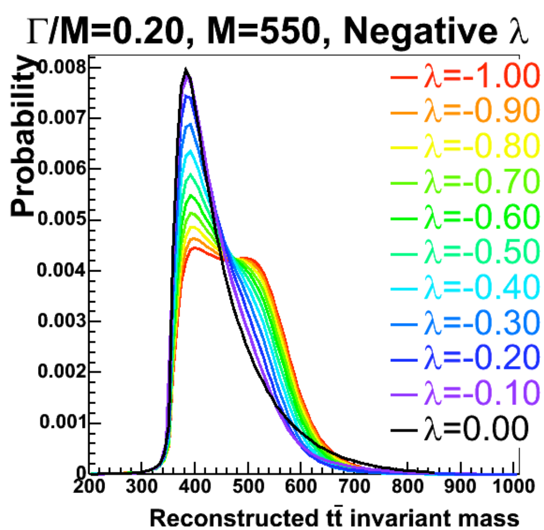


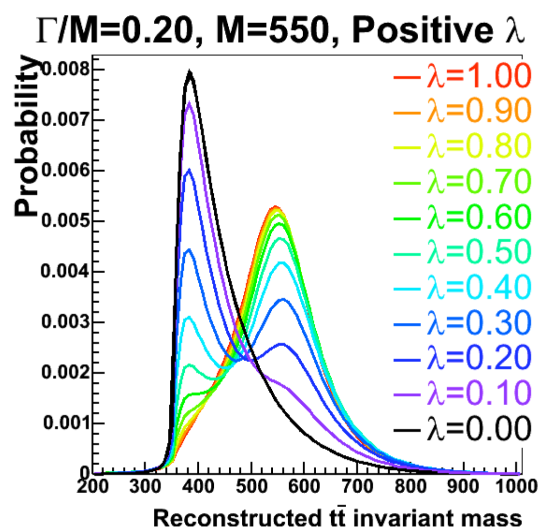


Convoluted with



BSM at CDF

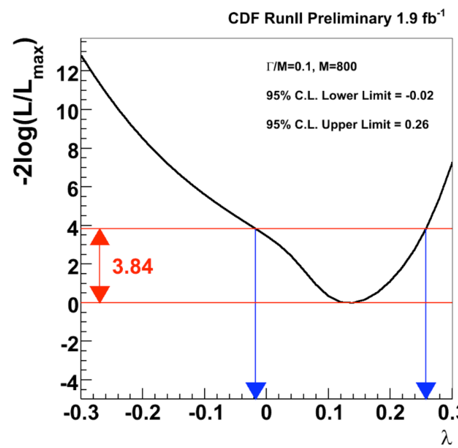




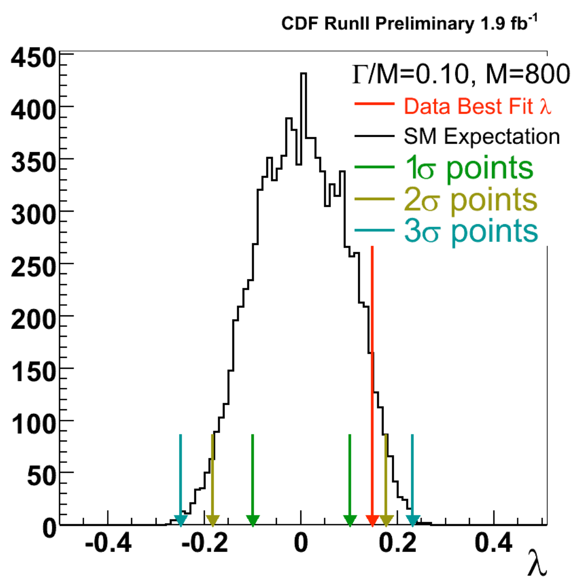
Likelihood function

$$L(\alpha,\nu_s,\nu_b) \equiv G(\nu_b;\nu_b^{\exp},\sigma_b^{\exp})P(N;\nu)\prod_{i=1}^{N}\frac{\nu_s P_s(\sqrt{s_{tt}}(i);\alpha)+\nu_b P_b(\sqrt{s_{tt}}(i))}{\nu}$$

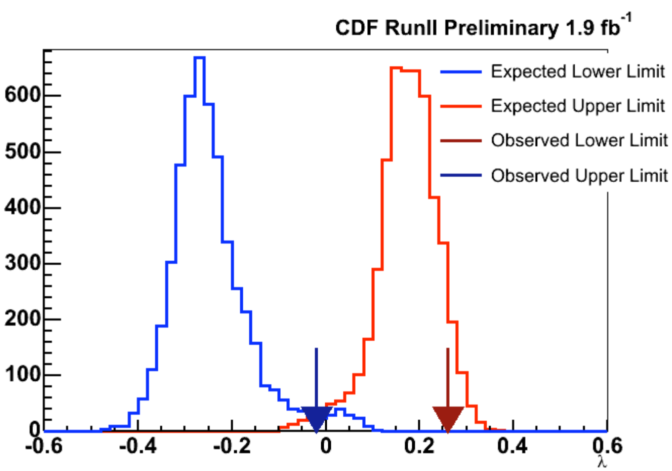
$$\alpha = (\lambda, M, \Gamma)$$



Running PE we can obtained the SM expectations from:



And the upper/lower limits



FCNC

Template fit parameters:

- Branching fraction B(t→Zq)
- Number of Z+jets events in the control region
- Shift in the ratio of Z+jets events in the signal regions vs. the control region (Gaussian constraint, 20%)
- Fraction of signal events in the "tagged" signal region
- Shift in jet energy scale

Fit Parameter $\left(\int L\,dt = 1.9\,\mathrm{fb}^{-1}\right)$	**Value**		
Branching Fraction, $\mathscr{B}(t \to Zq)$ (%)	-1.49	$\pm$	1.52
Z+Jets Events in Control Region, Z_{control}	129.0	$\pm$	11.1
Shift in Ratio Signal/Control Region, $\sigma_{\mathscr{R}_{\mathrm{sig}}}$	-0.61	$\pm$	0.60
Tagging Fraction, f_{tag} (%)	20.0	$\pm$	5.9
Jet Energy Scale Shift, σ_{JES}	-0.74	$\pm$	0.43

Stop: optimized event selection

Anti-Tagged Channel
20 GeV $< \not{E}_T$, 20 GeV $< P_T^{jet0}$, 20 GeV $< P_T^{jet1}$
20 GeV $< M_{\ell\ell}$, $H_T <$ 215 GeV + 325 GeV $\times \frac{\Delta\phi_{leps}\Delta\phi_{jets}}{\pi^2}$,
$\Delta\Phi(\not{E}_T$,jet OR lep) $> 20^0$ OR $\not{E}_T >$ 50 GeV

Events per 2000 pb^{-1} with Njet$\geq$ 2

Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
Top	4.38 ± 0.64	4.45 ± 0.66	9.85 ± 1.36	18.68 ± 2.46
Z+HF	0.26 ± 0.05	0.20 ± 0.04	0.07 ± 0.01	0.54 ± 0.10
Z+LF	9.33 ± 2.57	6.77 ± 2.10	3.13 ± 0.25	19.23 ± 4.91
Diboson	1.40 ± 0.25	1.05 ± 0.21	2.46 ± 0.45	4.91 ± 0.91
Fakes	1.65 ± 0.49	1.98 ± 0.59	5.02 ± 1.51	8.66 ± 2.60
SM Total	17.02 ± 3.01	14.46 ± 2.59	20.54 ± 3.28	52.02 ± 8.04
Data	20	6	20	46

Tagged Channel
20 GeV $< \not{E}_T$, 15 GeV $< P_T^{jet0}$, 12 GeV $< P_T^{jet1}$,
20 GeV $< M_{\ell\ell}$,

$$H_T \equiv \sum P_T < 215 \text{ GeV} + 325 \text{ GeV} \times \frac{\Delta\phi_{leps}\Delta\phi_{jets}}{\pi^2}$$

Events per 1900 pb^{-1} with Njet$\geq$ 2

Source	ee	$\mu\mu$	$e\mu$	$\ell\ell$
Top	8.43 ± 1.29	7.81 ± 1.20	20.26 ± 2.85	36.50 ± 5.27
Z+HF	1.02 ± 0.22	0.70 ± 0.15	0.27 ± 0.05	2.00 ± 0.43
Z+LF	0.63 ± 0.07	0.37 ± 0.07	0.24 ± 0.02	1.24 ± 0.12
Diboson	0.14 ± 0.02	0.10 ± 0.01	0.20 ± 0.03	0.44 ± 0.06
Fakes	0.39 ± 0.12	0.48 ± 0.14	1.48 ± 0.44	2.35 ± 0.70
SM Total	10.62 ± 1.49	9.46 ± 1.27	22.46 ± 2.88	42.53 ± 5.56
Data	10	11	24	45

Kinematic fitter (stop)

$$\chi^2 = \frac{\left(\vec{l}_{meas} - \vec{l}_{fit}\right)^2}{\sigma_l^2} + \frac{\left(\vec{\bar{l}}_{meas} - \vec{\bar{l}}_{fit}\right)^2}{\sigma_l^2} + \frac{(\vec{u}_{meas} - \vec{u}_{fit})^2}{\sigma_{uncl}^2}$$

$$+ \sum_{jets\,i} \frac{\left(\vec{j}_{i_{meas}} - \vec{j}_{i_{fit}}\right)}{\sigma_{jet_i}^2} + \frac{\left(M_{PP_1}^{fit} - M_{PP}^{assume}\right)^2}{\Gamma_{PP}^{hepg}}$$

$$+ \frac{\left(M_{PP_2}^{fit} - M_{PP}^{assume}\right)^2}{\Gamma_{PP}^{hepg}} + \frac{\left(M_{PP_1,l} - M_{\tilde{\chi}^\pm}\right)^2}{\Gamma^{\tilde{\chi}^\pm}}$$

$$+ \frac{\left(M_{PP_1,\bar{l}} - M_{\tilde{\chi}^\pm}\right)^2}{\Gamma^{\tilde{\chi}^\pm}} + \frac{\left(M_{PP_1,\bar{l},b_{jet}} - M_{PP_2,l,\bar{b}_{jet}}\right)}{\Gamma^{\tilde{t}}}$$